

Multiquark interactions and heavy hybrid stars

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Abstract

We introduce a two flavor Nambu–Jona-Lasinio (NJL) model with 8-quark interactions in the scalar and the vector channel. With the lower density region described by the density-dependent relativistic mean field model we construct a hybrid equation of state. We especially focus on the 4-quark vector couplings and the 8-quark vector NJL couplings and allocate a region in this parameter subspace where hybrid stars with masses larger than $2M_\odot$ exist.

1 Introduction

The recent discoveries of $2M_\odot$ compact stars [1, 2] push us to understand the nature of matter at high densities. It is possible that within very heavy compact stars there is a transition to quark matter. We focus on hybrid stars, composed of a nuclear envelope and a quark core.

In order to have a $2M_\odot$ star with a sizeable region of quark matter inside, quarks should have a low onset and the quark equation of state (EoS) should be stiff at high densities [3]. There are several microscopic mechanisms to introduce such a situation [4, 5, 6, 7, 8]. In this work we introduce one such mechanism: 8-quark interactions within the NJL framework [9, 10]. Although the 8-quark coupling naively scales as $1/N_c^2$ with respect to the 4-quark coupling (see Fig. 1), in a dense system the expectation value of the corresponding operator (e. g. the vector current operator) can be large. Therefore, 8-quark interactions should become important at high densities.

The hybrid equation of state (EoS) model has several parameters; we have considered a subspace of vector interactions in the quark sector. These are the 4-quark and the 8-quark vector interaction, quantified by dimensionless couplings, η_2 and η_4 , respectively. There are in general large uncertainties concerning the vector interactions for quark matter. We find a parameter space that allows for hybrid stars with masses higher than $2M_\odot$.

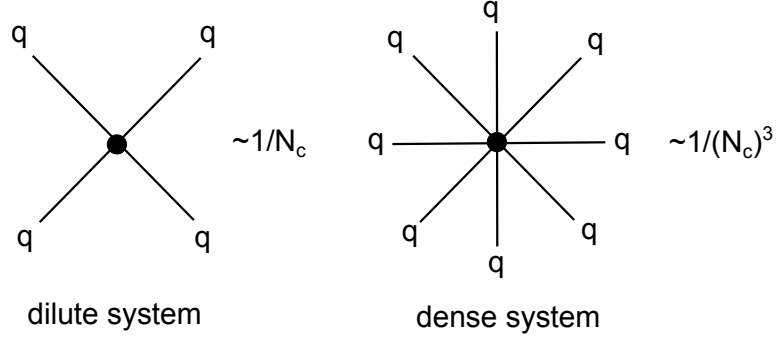


Figure 1: N_c scaling of 8-quark interactions.

2 Hybrid equation of state model

We consider a two flavor model of matter in beta equilibrium. Nuclear matter is described with the DD2 EoS, for details see [11]. Quark matter EoS is taken to be the NJL model with 8-quark interactions (NJL8) in the vector and in the scalar channel. The thermodynamic potential of the NJL8 model is

$$\Omega = U + \sum_{f=u,d} \Omega_f(M_f, T, \tilde{\mu}_f) - \Omega_0 , \quad (1)$$

where the classical and the one-loop contribution are

$$U = 2 \frac{g_{20}^2}{\Lambda^2} (\phi_u^2 + \phi_d^2) + 12 \frac{g_{40}^2}{\Lambda^8} (\phi_u^2 + \phi_d^2)^2 - 2 \frac{\eta_2 g_{20}}{\Lambda^2} (\omega_u^2 + \omega_d^2) - 12 \frac{\eta_4 g_{40}}{\Lambda^8} (\omega_u^2 + \omega_d^2)^2 , \quad (2)$$

$$\Omega_f = -2N_c \int \frac{d^3p}{(2\pi)^3} \left\{ E_f + T \log[1 + e^{-\beta(E_f - \tilde{\mu}_f)}] + T \log[1 + e^{-\beta(E_f + \tilde{\mu}_f)}] \right\} , \quad (3)$$

and ϕ_f and ω_f are scalar and vector mean-fields. More details on the model can be found in Refs. [9, 10] and references therein. The nuclear-quark phase transition is assumed to be first order. The important point about the nuclear sector is that DD2 is itself quite stiff, so maximum mass of a pure neutron star is already well above $2M_\odot$. In the quark sector the key role is played by the 8-quark vector interactions. Since they become relevant only at higher densities, the stiffness of quark matter is pronounced at higher densities, see Fig. 2. On the other hand, the onset of quark matter is controlled by the 4-quark vector interactions.

3 Masses and radii

We find that without vector interactions it is not possible to consider a hybrid star with $2M_\odot$ within this model. With finite vector interactions, several options for

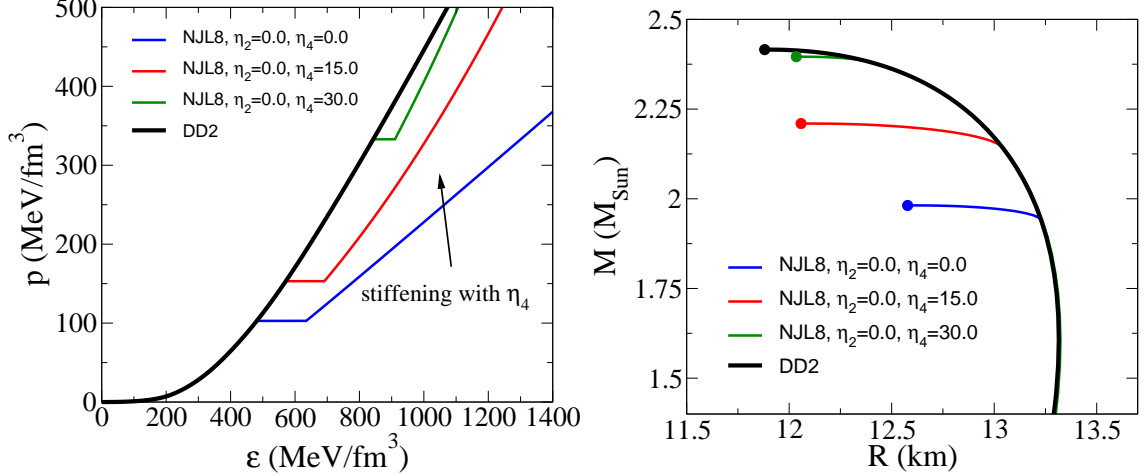


Figure 2: Left panel: EoS, Right panel: $M - R$ relationship. Results are shown for fixed $\eta_2 = 0.0$ and several η_4 .

achieving $M > 2M_{\odot}$ become viable. For example, on Fig. 2 we show the effect of 8-quark vector interaction on the maximum mass of a hybrid star. On Fig. 3 the possible star configurations within a parametric region spanned by η_2 and η_4 are shown. The lower values of η_2 and η_4 are excluded by the $2M_{\odot}$ constraint. Then, the upper bounds will in general be governed by causality, instability caused by the softening of the EoS at the transition, or the masquerade effect [12]. In the direction $\eta_2 = 0$ and $\eta_4 \geq 0$ we find the masquerade effect, which is also visible on Fig. 2. In the opposite direction $\eta_4 = 0$ and $\eta_2 \geq 0$ the appearance of quark matter makes the star unstable. However, within a limited window of η_2 it is still possible to recover a stable hybrid configuration by increasing η_4 . The speed of sound at densities reached in the cores of all stable configurations is below unity.

Note that in [10] the DD2 EoS was adjusted by an excluded volume contribution, but this is not the approach considered here. The main result found there was a large increase in the latent heat leading to third family hybrid stars in the mass-radii diagram.

4 Conclusion

We have shown that heavy hybrid stars can be obtained within the NJL model with 8-quark interactions. They represent a microscopic way of modeling very stiff quark matter at densities realizable in compact stars. The parametric diagram considered on Fig. 3 is very sensitive to the details of the nuclear-quark transition. For example, increasing the latent heat of the transition brings an interesting possibility of twin

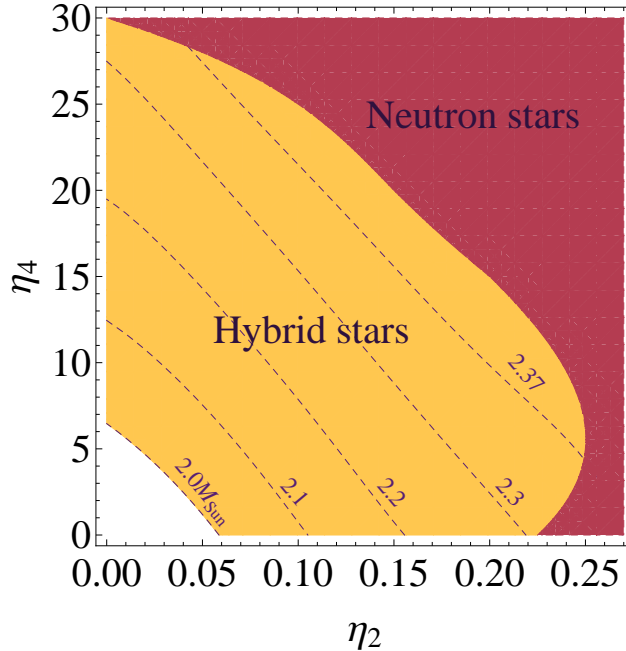


Figure 3: Composition of stars in the $\eta_2 - \eta_4$ plane. The curves denote maximum masses for hybrid stars.

stars at $2M_\odot$ [10]. It will be interesting to explore the role of strangeness [13]. Finally, the parameter window obtained here is likely to be reduced by further constraints on the vector interactions in quark matter [14, 15].

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